

'Augeye'

A Compact, Solid Schmidt Optical Relay For Helmet Mounted Displays

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ABSTRACT

Elegant design solutions for helmet mounted displays present a formidable challenge for the optical designer. Performance requirements are strict while space and weight allocations are at a premium. Recent advances in display technology and applications have accelerated the search for revolutionary designs in optical relays which are capable of relaying an optical stimulus to the eye with resulting high fidelity, field of view and ergonomic considerations. Eye relief, see-through capabilities, compactness, optical performance, robustness and type and size of display are all factors that greatly influence a design. This paper describes the optical design, fabrication and performance of a solid Schmidt prism used for relaying an optical signal or image to the eye while simultaneously providing the viewer with the capability to see-through to the outside world. It can be either of solid glass or plastic construction like a prism, or made of separate components. The novel aspect of this approach over previous designs is folding the system between the image and the Schmidt mirror as opposed to folding it at the image itself. This allows for a more compact design. The solid glass approach extends the apparent field of view to the viewer through refraction at the glass to air interface. If the spherical reflector of the Schmidt is rendered opaque, the viewer will only see the information provided by the optical stimulus. If partially reflective, the viewer can augment real world scenes with computerized symbology superimposed in the visual field. The stimulus may be either a high resolution CRT or a flat panel LCD.

1. INTRODUCTION

With the advent of virtual and augmented reality comes the need for sophisticated optical designs capable of relaying light from a display to an observer's eye. A myriad of requirements for an equal number of applications make these optical designs difficult from a designers standpoint. Eye relief, see-through capability, compactness, weight, optical performance, tolerance, field of view, brightness, cost to manufacture, robustness and type and size of display are all factors that greatly influence the optical design. Helmet mounted displays for medical applications may require resolution, weight, see-through and full color capability while applications for active immersion may require weight and field of view only. Telerobotic applications may have another set of requirements all together.

For a color application with high resolution and see-through requirements, field of view may be limited due to lack of suitable high definition color sources. A fixed number of pixels may be spread out over a certain field of view before pixelation becomes troublesome. For wide field of view applications with see-through capability, it becomes necessary to project the light, reflecting it off an optical element in front of the observer's eye; basic geometric principals work against the designer here, increasing size, volume and complexity of the optics. There exists a fundamental, geometric principal at work in helmet mounted display optics which is difficult to get around. Line of sight vision dictates that if an observer receives light from a specific field angle, there must be some optic in that path directing the light towards the eye. Compactness, and proximity to the eye is the key factor in keeping volume and weight down to a minimum.

This paper describes an optical design for a surgical instrument where high fidelity stereoscopic imaging, good color rendition, minimal volume and see-through capability are the performance aspects of highest importance. After investigation into many design configurations, a solid prism-like device was selected for its compactness, robustness and high performance. It is based on a very simple optical system known as the Schmidt camera.

2. DISCUSSION

Types of designs

The design of a helmet mounted display can follow one of two fundamental approaches; classical imaging, either direct view or projected via a beamsplitter, and a scanning method. The classical imaging technique is by far the most popular and requires a conventional display, (CRT or LCD), whose image is near collimated and relayed to the observer's eye. An advantage to the classical approach is the absence of moving parts. Limitations and problems arise from a lack of suitable displays (color, resolution, size, weight), and the bulk, cost and complexity of relay optics. Scanning techniques require a line or point source scanned in one or two dimensions respectively to paint a full picture on the observer's retina. Conventional optics are still required to collimate the light and relay it to the observer's eye. The advantages of the scanning approach is that it can simplify the relay optics, up to a pupil, by reducing the field requirement. Reflective optics can be used for scanning design, utilizing principals unique to reflective systems which are difficult to duplicate with

refractive optics. Disadvantages of scanning systems are the requirement for moving parts and the current lack of suitable blue and green coherent light sources capable of high frequency pulsing.

Limitations

The single most fundamental factor limiting the simplicity and compactness of an optical design for helmet mounted displays is the direct, line of sight requirement. If an observer receives light from a specific field angle, there must be some optic in that path directing the light towards the eye. Light cannot come from empty space. Ultimately, the observer's eye is the systems pupil. For the observer to have a half field of view Θ , the optic, a distance z away, must have a minimum diameter of $d = 2z \tan(\Theta)$. This is true for classical or scanning systems incorporating reflective or refractive optics. The larger the desired field of view, the larger the optic need be for a given distance. Figure 1 shows this principle.

Symmetry

The principle of symmetry is a very powerful tool in the design of optical systems. However, symmetry in reflective systems can result in obscurations and or folded beamcombiner optics resulting in awkward designs with low throughput. Extensive use of aspherics and tilted or decentered elements can result in more elegant looking designs but the price is high in cost, especially for wide fields of view.

When utilizing symmetry in the design of helmet mounted displays, recognizing that the eye defines the systems exit pupil is probably the most fundamental insight. Although many design approaches may successfully be employed to achieve symmetry, an expedient and elegant solution to achieving symmetry, field of view and simplicity is the Schmidt camera, (Figure 2). The Schmidt is a simple and powerful optical design which places the pupil at the center of curvature of a spherical mirror. Due to the inherent symmetry of spherical mirrors about the center of curvature light from all fields are treated the same. Therefore, all fields are indistinguishable from an axial source and only spherical aberration needs to be controlled. If the mirror is slow enough, no correction is necessary. The speed of the system is dependent upon the focal length of the mirror and the diameter of the pupil (eye). The advantage to this design is wide field capability and lack of field aberrations. The

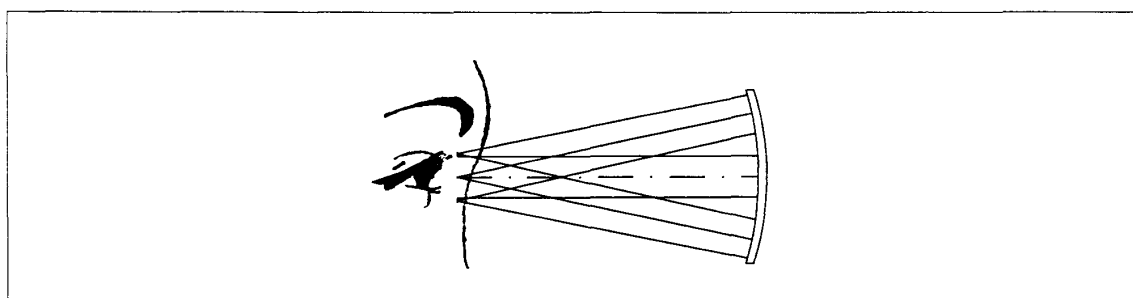


Figure 1. Light at an observer's eye from some field point must come from an optic. The closer the optic is to the eye, the smaller it is for a given field angle.

disadvantage is that the image surface lies on a convex sphere concentric with the mirrors center of curvature.

Three possibilities exist for utilizing the Schmidt configuration. The first possibility is to use a curved display such as a CRT with a fused coherent fiber bundle face at the correct curvature. The second possibility is to use a field lens to flatten the image plane; both solutions require folding the optical train mid way between the image plane and the spherical mirror. The third possibility is to re-image a display with the appropriate Petzval curvature, matching the input to the Schmidt. A modified eyepiece design with the exit pupil at the center of curvature of the concave image surface works quite well for this but requires a significant number of optical elements. The third approach, or a derivation thereof, is the most popular when incorporating the Schmidt principal into helmet mounted designs. Figure 3 shows an example of a flat display, relayed into a Schmidt system via a modified eyepiece. This approach typically folds the optical path at or near the curved focal plane. The simplest, most elegant solution is to incorporate one of the first two of the foregoing possibilities stated above, reducing the number of elements, volume, cost and size; the price paid for this approach is in reduced field of view.

Augeye: Augmented Eye

This small device whose name is derived from its ability to augment real world information with symbology or supplemental information via a display, is a solid Schmidt based design used to relay an optical signal or image to the eye while simultaneously providing the viewer with the option to see-through the device to the outside world. The device can be either of solid glass or plastic construction like a prism, or made of separate components. There are two novel aspects of this approach over previous designs of similar type. The first is folding the Schmidt system between the

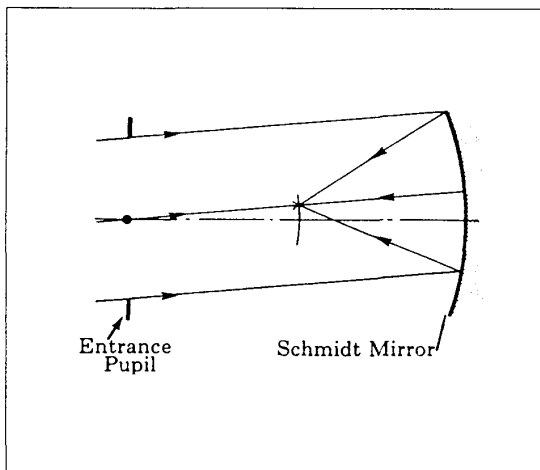


Figure 2. Schmidt Camera. Stop at Spherical Mirrors Center of Curvature.

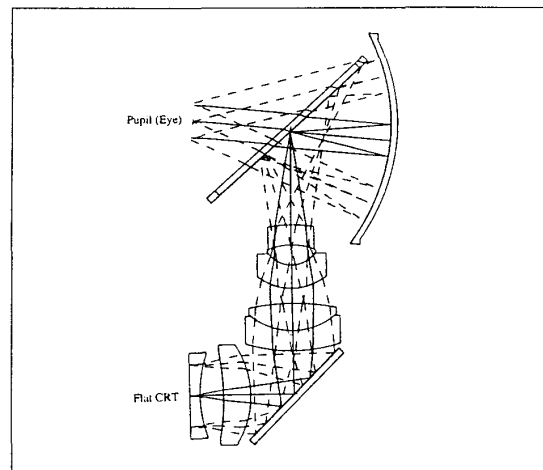


Figure 3. Typical See-Through Goggle Design Incorporating Schmidt Relay and Modified Eyepiece with Pupil at Center of Intermediate Curved Image Surface.

image and the mirror as opposed to folding it at the image itself, moving the focal plane out of the optical path and allows for a more compact design. The second is taking advantage of the glass to air interface near the eye to increase the apparent field of view. Light heading towards the eye, bends away from the normal as it exits the glass, increasing the angle of incidence at the pupil. If the spherical reflector of the Schmidt is rendered opaque, the viewer will only view the information provided by the optical stimulus. Here and after, the optical stimulus will be referred to as the CRT, although it may be any type of light source or intermediate image.

In its simplest form, the Augeye device has two spherical surfaces and a beamsplitter surface at a 45 degree cemented interface. Figure 4 shows the solid Schmidt relay prism. The surface S_1 is the curved surface of the CRT, which matches the glass radius at the surface.

Surface S_1 is the entrance surface to the Schmidt. The light enters the solid Schmidt and is partially reflected by the cemented beamsplitter surface S_2 towards the concave spherical Schmidt mirror S_3 . Surface S_3 is partially reflective so that it reflects part of the signal back to the eye E_1 , while simultaneously allowing light to pass through from the outside scene at A. The image surface S^1 is approximately half the radius of curvature of surface S_3 and is at an approximate distance of half the radius of curvature from S_3 such that the light is collimated upon reflection. These values are approximate since the solid Schmidt is not contiguous to the pupil. The viewer's eye is located at the pupil of the system which is at the apparent center of curvature of surface S_3 . The glass does not extend all the way to the pupil and is cut short at surface S_4 to provide eye relief, weight reduction and an increase in apparent field of view upon refraction from a medium of high index (glass) to that of lower index (air). Due to the nature of the Schmidt system, the device suffers only from spherical aberration and is free of field aberrations. A 30 x 30 degree field of view is possible with the compactness shown. The system was designed with a 10 mm pupil to allow for eye movement

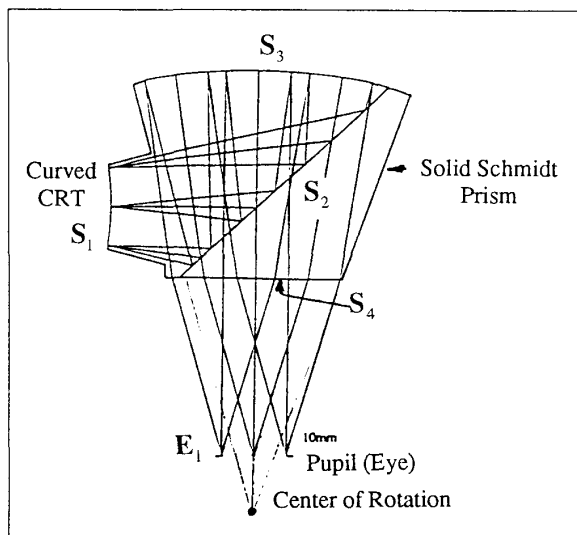


Figure 4. Solid Schmidt Relay with Curved Image Plane.

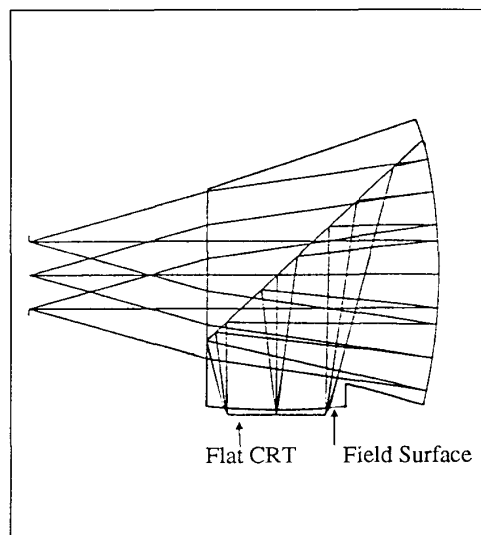


Figure 5. Solid Schmidt Relay with Field Flattening Surface.

while scanning off axis fields; however, the eye rarely gets larger than 7mm in diameter. This system has less than 0.2 waves rms of aberration throughout the full field for a 7mm pupil diameter. In most cases, the eye is 3 to 4 mm in diameter and the system is near diffraction limited. The only chromatic aberrations occur at the glass-air interface S4 and should not be a problem for a full color display provided that a miniature, curved color display can be obtained. The limitations in this example are the fixed conjugate stemming from the fact that the CRT fits up against the glass prism, the limited field of view and the requirement for a curved CRT. Figure 5 shows the same type of solid prism as in figure 4, but with a field flattening surface near the flat CRT. The solid Schmidt prism display with field flattener suffers from lateral chromatic aberration and may be used successfully with a monochrome input without design modifications. This design has approximately a 33 X 33 degree field of view and a flat 1/2 X 1/2 inch CRT face. The Solid Schmidt is made of Ohara SFL03 because of its high index of refraction. The high index of SFL03 is desired to increase the refraction at surface S4 which increases the apparent field of view to the viewer. For a fully dilated pupil of 7 mm this design has about 0.5 waves of aberration at full field. The actual Schmidt prism can be cut such that the viewer cannot directly view the CRT surface. The sides can also be cut such that when the viewer's eye is rotated to look at the edge of the glass prism, the sides are cut at the same angle, thus making the prism basically transparent to the viewer. All the viewer sees is a slight discoloration while looking through the glass. He does not see the edges of the prism because they lie along his line of sight. This prism angle can be calculated when using the pivot point of the eye to be an average of 10 mm behind the pupil. The entire Schmidt element can be rendered powerless in transmission by cementing a thin plano/concave element of like glass over the coated surface S₃. This makes the solid Schmidt appear to be a piece of solid glass in transmission with two plane and parallel sides. The element would have no power in transmission and objects viewed through the prism would appear to be of correct size, although slightly displaced.

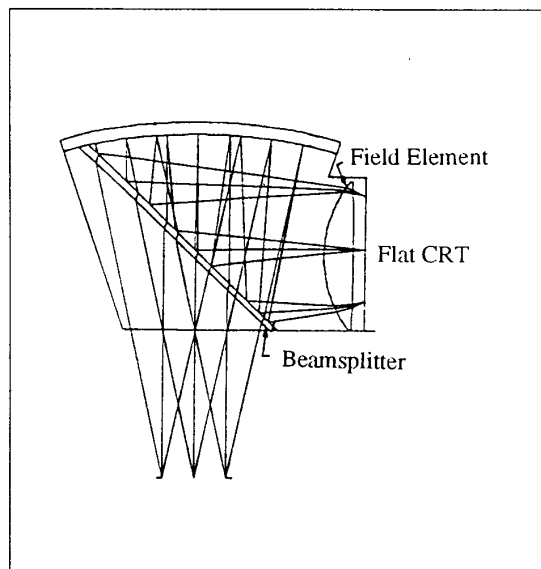


Figure 6. Folded Schmidt with Separate Elements.

Figure 6 shows the same type of design as described above but instead of a solid prism, this design has a separate beamsplitter element and Schmidt reflector. The principal is the same in that the CRT lies off to the side of the unit but it is no longer a solid piece of glass. The advantage of this separate element design is that it does not suffer from lateral chromatic aberration and thus can be with a color display. The disadvantage to the separate element design is the reduced apparent field of view since there is no gain in angle due to the refraction at the glass/air interface of the solid design. The separate element approach has about a 20 X 20 degree field of view for a half inch CRT. The front surface of the Spherical reflector can be curved to provide zero power in transmission.

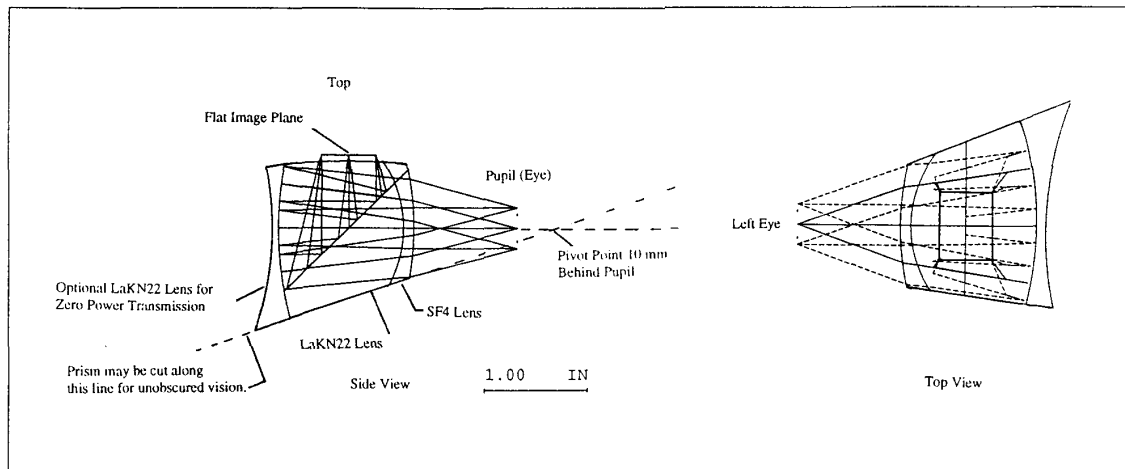


Figure 7a. Solid Schmidt Cemented Doublet.

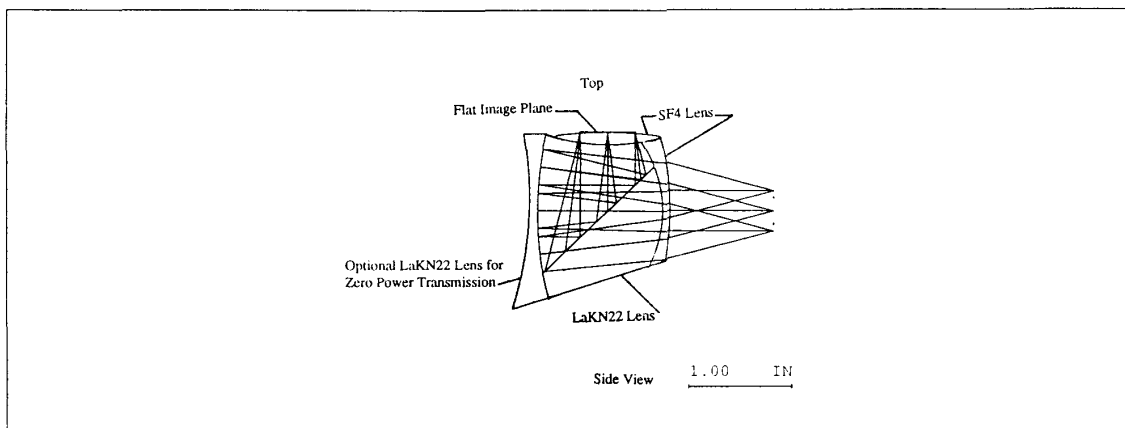


Figure 8a. Solid Schmidt Cemented Triplet.

Figures 7a and 8a show color corrected versions of the solid Schmidt design with a cemented doublet and triplet respectively. Both of these designs have a focal length of 1 inch, utilize a flat color display and exhibit about 10 percent barrel distortion. The doublet cements an SF4 lens on the viewers side of the Schmidt prism which is made of LaKN22. The field of view is 40 horizontal by 30 vertical. At a 6 mm diameter pupil, polychromatic performance (red, green, blue) ranges from 0.15 waves rms on axis to 0.9 waves rms at the corner of the field (25 degrees off axis). The cemented triplet uses another SF4 element cemented near the CRT for improved performance. Polychromatic wavefront analysis for the cemented triplet ranges from 0.2 waves rms on axis to 0.6 waves rms at full field. The triplet represents a 1.5x improvement in performance off axis over the doublet. Spot diagrams, diffraction encircled energy and polychromatic MTF curves for the doublet and triplet designs are shown in figures 7 and 8 b, c, and d respectively.

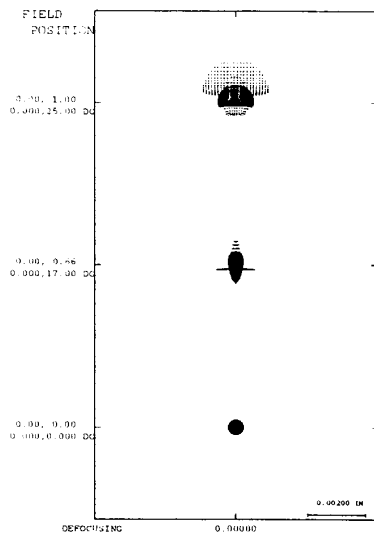


Figure 7b. Cemented Doublet Spot Diagrams.

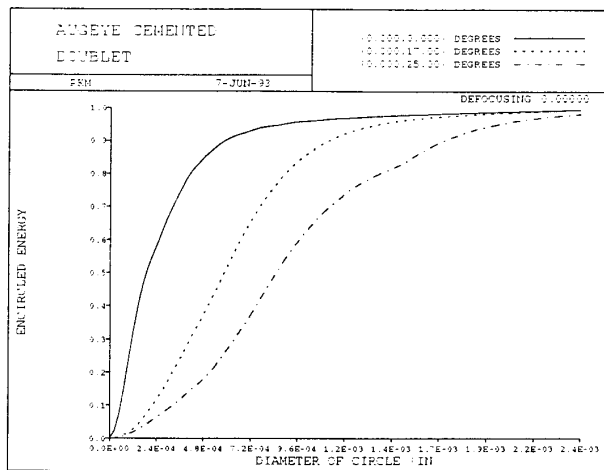


Figure 7c. Cemented Doublet Encircled Energy.

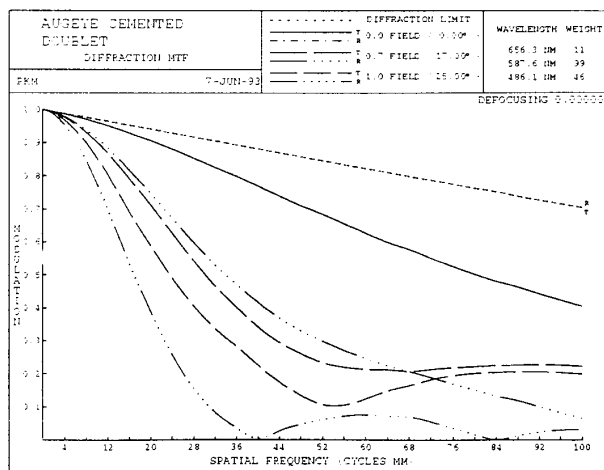


Figure 7d. Cemented Doublet MTF.

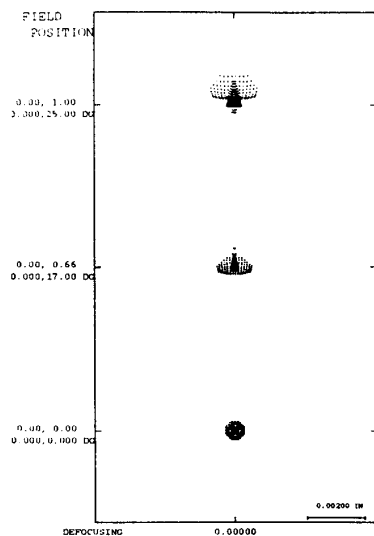


Figure 8b. Cemented Triplet Spot Diagrams.

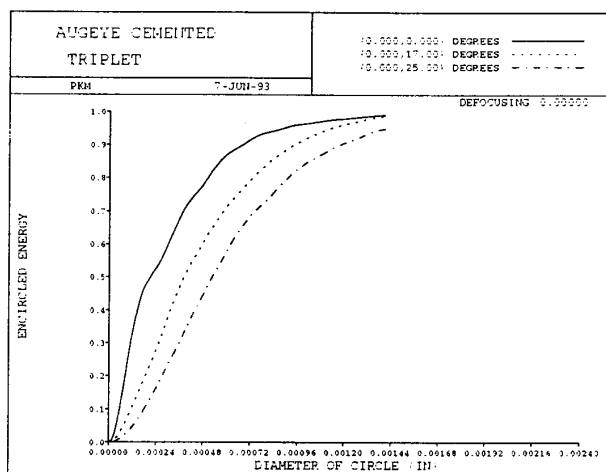


Figure 8c. Cemented Triplet Encircled Energy.

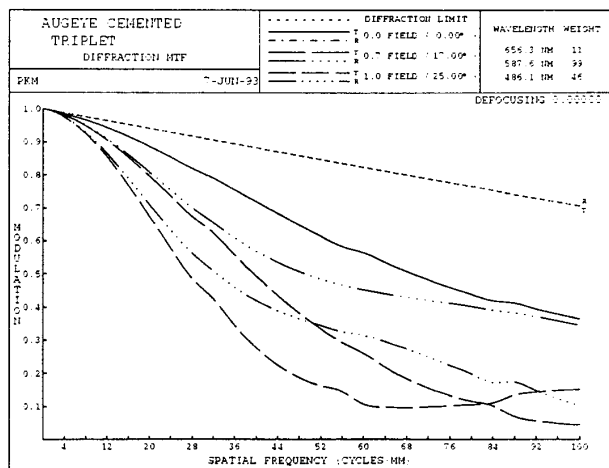


Figure 8d. Cemented Triplet MTF.

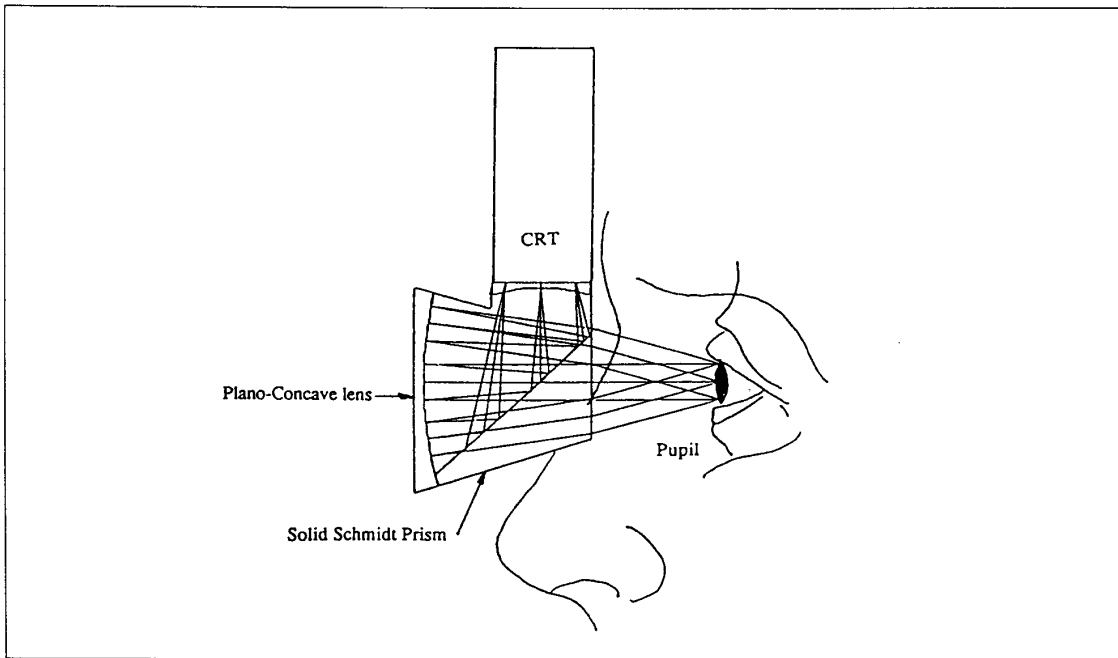


Figure 9. Solid Schmidt with Human Interface.

There are several inherent advantages in a super compact folded Schmidt design. Previous see-through designs required many optical elements to relay the CRT image to the eye, (known as relay and combiner optics). Large beamsplitter/combiner optics are typical of former design types. The innovative design described here moves the CRT face close to the eye and eliminates all but one of the optical elements previously required. The optical element counted here is the solid Schmidt Prism. It also puts the relay and combiner optics into a solid piece of glass thus making them less susceptible to misalignment. The size of the prism is reduced by putting the CRT face on the edge of

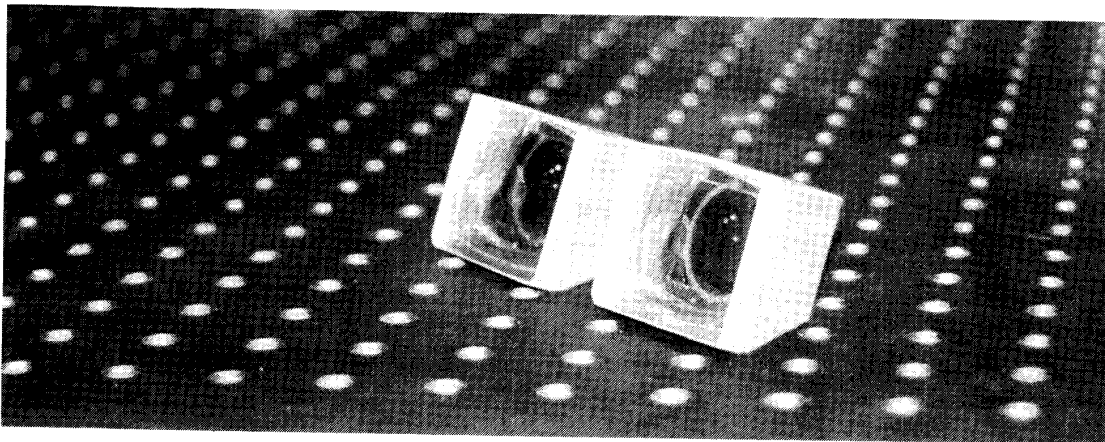


Figure 10. Solid Schmidt Prisms Fabricated out of SFL03 with Field Flattening Surface.

the prism instead of relaying it to the vicinity of a beamsplitter surface as some of the other designs do. The CRT to prism edge approach reduces the size of the Schmidt system by at least a factor of two. Previous designs would relay the CRT face to the beamsplitter in the (non-solid) Schmidt system which is located exactly half way between the Schmidt mirror S3 and the viewer's eye E1. In the solid Schmidt described, the cemented beamsplitter is one quarter the distance from the mirror to the eye, which allows for the design's compactness. In addition, making the prism out of high index glass reduces its size for a given field of view. The larger the index of refraction, the greater the angle of refraction at surface S4 and the larger the field of view. Figure 9 shows a side view of the device with a human interface. The CRT is mounted above the head instead of to the side to provide the viewer with an unobstructed side view which is more important in most situations than upward vision. The whole prism/CRT module can be supported by a fairly lightweight headset. Adjustment for interpupillary distance, angle of eye convergence and alignment for stereoscopic vision is simplified because the entire device is a solid piece that can be multi-axially translated and rotated. There are no separate elements to get out of alignment. Figure 10 shows a photograph of a pair of solid Schmidt prisms fabricated for evaluation. The glass is SFL03 and is shown pictorially in figure 5. Image quality with a green 1 inch square CRT, (1000x1000 lines) was sharp out to 30 degrees but lateral color impaired the full field imagery. It is recommended that a filter be used with this particular design to narrow the CRT bandwidth. The cemented doublet and triplet were designed after fabrication of these prisms but performance is expected to be superb out to 50 degrees.

3. CONCLUSIONS

This paper describes an innovative compact optical design for a helmet mounted display requiring see-through capabilities. A solid glass approach extending the apparent field of view. This design enables one to augment the real world as seen through the prism with supplemental information as given by the CRT which could be computer generated or photographic. Applications lie in the field of 'augmented reality', medical imaging, entertainment and computer-aided manufacturing and design. It represents an interesting design for display optics due to its compactness, solid design, high fidelity, large field of view, and transparency to the viewer. Although other display optics have utilized solid beamsplitter prisms in front of the eye to combine and direct energy from a remotely located CRT, this device is the first to use a solid Schmidt with the CRT on a side face for compactness, simplicity and high performance.

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